EUROPEAN PATENT APPLICATION

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(54) Polarization-independent optical wavelength selective coupler.

(57)   A double-periodic grating is described for obtaining polarization- independent filtering and coupling. The grating may be viewed as a combination of two gratings with slightly different grating periods. The two periods are carefully chosen to match the difference in propagation constants of the TE and TM polarization modes such that both modes are coupled at the same wavelength. A novel method of obtaining a double-periodic grating is described. Use in optical waveguide vertical couplers and filters is described.
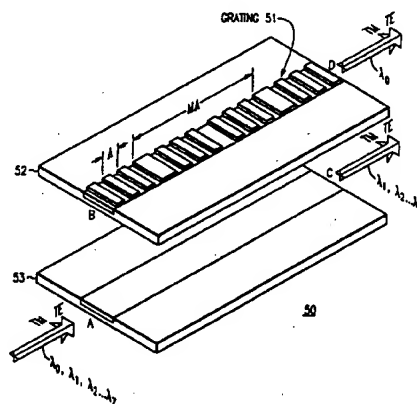
FIG. 5

EP 0 647 861 A1

Technical Field

This invention relates to grating-assisted optical wavelength selective couplers and, in particular, to couplers that are insensitive to the state of polarization of the incident signal.

Background of the Invention

In order to use wavelength division multiplexing techniques in optical transmission systems, one requires efficient, narrow-band optical wavelength filters. In a paper entitled "Grating-assisted In-GaAsP/InP vertical codirectional coupler filter" by RC. Alferness et al., published in the 6 November 1989 issue of Applied Physics Letters 55(19), pp. 2011-2013 there is described a four-part channel-dropping filter employing grated-assisted coupling between asynchronous optical waveguides. However, such devices are polarization dependent and will respond differently for the TE and TM modes. As a consequence, the amplitude of the dropped channel will fluctuate in such devices as the polarization of the input signal varies. Accordingly, it is the object of the present invention to provide optical filters that operate independently of the state of polarization of the incident light.

Summary of the Disclosure

In accordance with the present invention, polarization independent filtering is obtained by means of a double-periodic grating structure which may be viewed as a combination of two gratings with slightly different grating periods. The two periods are carefully chosen to match the difference in propagation constants of the TE and TM modes such that both are coupled at the same wavelength.

It is shown that the double-periodic grating can be realized by multiplying two square wave grating functions, thus simplifying the fabrication of such devices.

The principal of the invention can be applied equally to both two and four-port filters operating either in the transmission or reflection mode.

Brief Description of the Drawings

FIG. 1 shows a prior art grating-assisted optical wave coupler;

FIG. 2A shows the optical response of a double-periodic filter;

FIG. 2B shows the optical response of a double-periodic filter wherein the TE and TM modes share a common transmission band;

FIGS. 3 and 4 illustrate how a double-periodic grating is formed by multiplying rectangular gratings of different periodicity;

FIG. 5 shows a four-port filter in accordance with the teachings of the invention; and

FIGS. 6, 7 and 8 show alternate embodiments of the invention.

Detailed Description

Referring to the drawings, FIG. 1 shows a prior art grating-assisted, optical coupler comprising two, vertically coupled, optical waveguides 10 and 11. Essentially, the device comprises two, single-mode, asynchronous waveguides (i.e., having greatly different propagation constants, $\beta_2 > \beta_1$) that are efficiently coupled in the forward direction by means of a periodic coupling grating 12. For a more complete description of such devices, see the article by R.C. Alferness et al., entitled "Vertically coupled In-GaAsP/InP buried rib waveguide filter", published in the 11 November 1991 issue of Applied Physics Letter, 59(20), pp. 2573-2575.

If the grating period Λ is chosen such that

$$\Lambda = 2\pi/(\beta_2 - \beta_1) \quad (1)$$

there will be a wavelength λ_0 at which light will be completely coupled between the two waveguides where

$$\lambda_0 = (n_2 - n_1)\Lambda \quad (2)$$

and n_1 and n_2 are the refractive indices of waveguides 10 and 11 respectively. Thus, if signals at wavelengths $\lambda_0, \lambda_1, \lambda_2, \lambda_3...\lambda_z$ are coupled into the filter, the dropped channel, at wavelength λ_0, will appear at the output of waveguide 11, whereas the balance of the signals, $\lambda_1, \lambda_2, \lambda_3...\lambda_z$ will appear at the output end of waveguide 10. The optical bandwidth of this type of wavelength-dependent coupler is inversely proportional to the number of grating periods.

Such grating-assisted directional couplers have previously been demonstrated in InP with optical bandwidths as low as 1.7nm at wavelengths of 1.5μm. However, as noted above, these couplers are strongly sensitive to the polarization of the incident light. Typically, coupling for the TE-polarized input light occurs at longer wavelengths than for TM-polarized input light. The difference in wavelength

$$\Delta\lambda = \lambda_{0(TE)} - \lambda_{0(TM)} \quad (3)$$

can be as much as 30nm and, hence, substantially larger than the filter bandwidth. This wavelength shift arises because of the inherent difference in the birefringence for the two waveguides. In particular, the birefringence, $n_{2(TE)} - n_{2(TM)}$, in the higher index guide is usually much higher than the birefringence, $n_{1(TE)} - n_{1(TM)}$, the lower index guide, where

$$n_i = \beta_i \lambda/2\pi \quad (4)$$

denotes the effective phase indices of the two waveguides, $i = 1$ and 2.

Inasmuch as

$$\lambda_{0(TE)} = [n_{2(TE)} - n_{1(TE)}]\Lambda \quad (5)$$

and

$$\lambda_{0(TM)} = [n_{2(TM)} - n_{1(TM)}]\Lambda \quad (6)$$

it is apparent that $\lambda_{0(TE)} = \lambda_{0(TM)}$ only if the two wave-

guides exhibit the same birefringence. In practice, however, it is difficult to fabricate two waveguides that have substantially different propagation constants but equal birefringence. In an alternative solution to this problem, in accordance with the present invention, the equivalent of a double-periodic coupling grating is employed. This grating structure essentially introduces two different coupling periods Λ_{-1} and Λ_1 where

$$\Lambda_{-1} < \Lambda < \Lambda_1. \quad (7)$$

For each polarization mode, the filter then exhibits two transmission bands centered at wavelengths $\lambda_{1(TM)}$, $\lambda_{-1(TM)}$, and $\lambda_{1(TE)}$, $\lambda_{-1(TE)}$ respectively, where

$$\lambda_{1(TM)} = (n_{2(TM)} - n_{1(TM)})\Lambda_1 \quad (8)$$
$$\lambda_{-1(TM)} = (n_{2(TM)} - n_{1(TM)})\Lambda_{-1} \quad (9)$$
$$\lambda_{1(TE)} = (n_{2(TE)} - n_{1(TE)})\Lambda_1 \quad (10)$$

and

$$\lambda_{-1(TE)} = (n_{2(TE)} - n_{1(TE)})\Lambda_{-1}. \quad (11)$$

This is illustrated in FIG. 2A which shows the optical response of a double-periodic filter for the two modes. In accordance with the invention, the grating is designed so that the two modes share a common transmission band centered at an operating wavelength λ_{op}. This is illustrated in FIG. 2B where

$$\lambda_{op} = \lambda_{1(TM)} = \lambda_{-1(TE)} \quad (12)$$

or, from equations (8) and (11),

$$\lambda_{op} = \Lambda_1(n_{2(TM)} - n_{1(TM)}) \quad (13)$$
$$\lambda_{op} = \Lambda_{-1}(n_{2(TE)} - n_{1(TE)}). \quad (14)$$

Knowing the refractive indices at the wavelength λ_{op}, the grating periods Λ_1 and Λ_{-1} can be determined. The useful spectral range, however, is limited to the wavelength span between $\lambda_{1(TE)}$ and $\lambda_{-1(TM)}$ because of the additional transmission bands at those wavelengths which are strongly polarization dependent. Thus, in accordance with the present invention the difference in the birefringence between the two waveguides is advantageously as large as possible.

Having established the conditions for polarization-independent coupling, the remaining problem is how to fabricate a grating having the required double periodicity Λ_1, and Λ_{-1}. In accordance with the present invention this can be done in either of two equivalent ways.

From the trigonometric corollary

$$2 \sin x \cos y = \sin(x + y) + \sin(x - y) \quad (15)$$

it is seen that the product of two largely different sinusoids is equivalent to the sum of two slightly different sinusoids. If $\sin x$ corresponds to the relatively fine grating Λ, and $\cos y$ corresponds to the relatively course grating of period $M\Lambda$, equation (15) can be rewritten as

$$2 \sin K_0 x \cos K_0 x/M = \sin K_{-1}x + \sin K_1 x \quad (16)$$

where

$$K_0 = 2\pi/\Lambda \quad (17)$$
$$K_1 = 2\pi/\Lambda - 2\pi/M\Lambda = K_0(1 - 1/M) = 2\pi/\Lambda_1$$
$$(18)$$

and

$$K_{-1} = 2\pi/\Lambda + 2\pi/M\Lambda = K_0(1 + 1/M) = 2\pi/\Lambda_{-1}$$
$$(19)$$

Then, from equations (18) and (19), we obtain

$$2/\Lambda = 1/\Lambda_1 + 1/\Lambda_{-1} \quad (20)$$
$$M\Lambda = 2[1/(1/\Lambda_1 - 1/\Lambda_{-1})] \quad (21)$$

where M is any arbitrary number greater than one. Advantageously, M lies between 5 and 10.

Having demonstrated that the product of two gratings, of periods Λ and $M\Lambda$, is the equivalent of the sum of two gratings of wavelength Λ_1 and Λ_{-1}, one can construct a filter in either of two ways. As a practical matter, however, it is difficult to fabricate a grating by multiplying the fine grating of period Λ with a sinusoidal coarse grating of period $M\Lambda$. This would result in a structure that is the equivalent of a one hundred percent amplitude-modulated wave. Such a complicated structure would require height variations of the grating that would have to be constructed with high accuracy. By contrast, a grating structure formed by multiplying a sinusoidal, or square-wave fine grating with a rectangular square-wave coarse grating can be much more easily fabricated. While this gives rise to higher order grating components, these are out of the band of interest and can be ignored. Thus, FIG. 3, now to be considered, shows a fine, uniform grating of wavelength Λ, multiplied by a symmetric square wave function 31 varying between +1 and -1 and period $M\Lambda$.

For purposes of illustration, M was chosen equal to 5, and the phase of the modulating wave 31 was selected to switch between +1 and -1, in phase with the fine grating 30. In the intervals +1 and -1, the fine grating is unaffected. The transition ±1 and ∓1, however, introduces a 180° phase shift in the fine grating, thus modifying the fine grating as shown at the transition points 1, 2 and 3 along curve 32 in FIG. 3. It will be noted that the amplitude of the fine grating is unaffected. Only the distribution of the grating is modified. That is, instead of having a grating element at point 1, the next grating element occurs a half cycle or 180° later relative to the distribution of the grating element along curve 30. The net result, as explained herein above, is to produce the equivalent of a sinusoidal double-periodic grating.

Changes in the phase of the modulating wave relative to the fine grating produce gratings that are physically different in the transition interval. This is shown by curve 40 in FIG. 4, which is the result of shifting curve 41 relative to the fine grating 42. However, the response of the filter is the same. Basically, all that is required to produce the desired double-periodic grating is that a 180° transition occur between intervals of uniform grating.

FIG. 5 shows a four-port, vertically-stacked, forward-coupling filter 50 incorporating a double-periodic grating 51 in accordance with the present invention. Incident light waves, at wavelengths λ_0, λ_1, $\lambda_2...\lambda_z$, en-

ter the lower left port A of the filter in both the TE and TM modes. The dropped channel, at wavelength λ_0, leaves the filter by way of the upper right port D of upper waveguide 52. Being polarization independent, both modes are preserved and exit together. The remaining signals λ_1, $\lambda_2...\lambda_z$ continue along the lower waveguide 53 and exit via port C.

The illustrative embodiment shown in FIG. 5 is, as noted, a forward-coupled, four-port filter. However, the double-periodic grating is not limited to such devices. The invention can, just as readily, be incorporated into reverse-coupled, four-port filters, and reverse-coupled, two-port filters. These are illustrated in FIGS. 6, 7 and 8, which show, symbolically, a forward-coupled four-port filter, a reverse-coupled four-port filter, and a reverse-coupled two-port filter.

Referring to FIG. 6, the two lines 61 and 62 represent the two wavelengths, and the vertical lines 63 between the wavepaths represent the grating. The input signal is applied to port A. The dropped channel appears at port D, and the remaining channels exit at port C.

For this filter, the relation between the transmission bands for each of the modes, and the grating periods were given by equations (8), (9), (10) and (11). To design a reverse-coupled, four-port filter, as represented in FIG. 7, n_1 in the several equations is replaced by $-n_1$ and the equations become

$$\lambda_{1(TM)} = (n_{2(TM)} + n_{1(TM)})\Lambda_1 \quad (22)$$
$$\lambda_{-1(TM)} = (n_{2(TM)} + n_{1(TM)})\Lambda_{-1} \quad (23)$$
$$\lambda_{1(TE)} = (n_{2(TE)} + n_{1(TE)})\Lambda_1 \quad (24)$$

and

$$\lambda_{-1(TE)} = (n_{2(TE)} + n_{1(TE)})\Lambda_{-1}. \quad (25)$$

In a grating design based upon these equations, a signal applied to port A of waveguide 71 will divide between port C and port B of waveguide 72.

In the two-port case, illustrated in FIG 8, there is only one waveguide. Hence, $n_2 = n_1$. In the forward-coupled case, where n_1 is positive, all the equations reduce to zero, indicating that a forward-coupled, two-port filter cannot be realized In the case of a reverse-coupled, two-port filter, the equations become

$$\lambda_{1(TM)} = 2n_{(TM)}\Lambda_1 \quad (26)$$
$$\lambda_{-1(TM)} = 2n_{(TM)}\Lambda_{-1} \quad (27)$$
$$\lambda_{1(TE)} = 2n_{(TE)}\Lambda_1 \quad (28)$$
$$\lambda_{-1(TE)} = 2n_{(TE)}\Lambda_{-1}. \quad (29)$$

While reference was made to a vertically-stacked filter, the invention is not limited to this particular configuration. In general, the two waveguides can be arranged along side each other, or in any other convenient configuration.

Claims

1. A grating having a double-periodicity comprising:
   a plurality of grating sections, each having a uniform periodicity Λ, separated by 180° phase shifts.

2. The grating according to claim 1 wherein:
   said 180° phase shifts occur at intervals equal to $M\Lambda$, where M is any arbitrary number greater than one.

3. A polarization-independent coupler comprising:
   a pair of asynchronous optical waveguides in coupling proximity; and
   a grating according to claim 1 distributed along one of said waveguides.

4. A polarization-independent filter comprising:
   an optical waveguide; and
   a grating according to claim 1 distributed therealong.

5. The grating according to claim 2 wherein: said grating is equivalent to a grating having a double-periodicity Λ_1 and Λ_{-1} where:
   $$2/\Lambda = 1\Lambda_1 + 1/\Lambda_{-1}$$
   $$M\Lambda = 2[1/(1/\Lambda_1 - 1/\Lambda_{-1})].$$

6. A polarization-independent coupler comprising:
   a pair of asynchronous optical waveguides in coupling proximity; and
   a grating according to claim 5;
   characterized in that:
   said grating is polarization-independent at an operating wavelength λ_{op} given by
   $$\lambda_{op} = \Lambda_1(n_{2(TM)} - n_{1(TM)})$$
   and
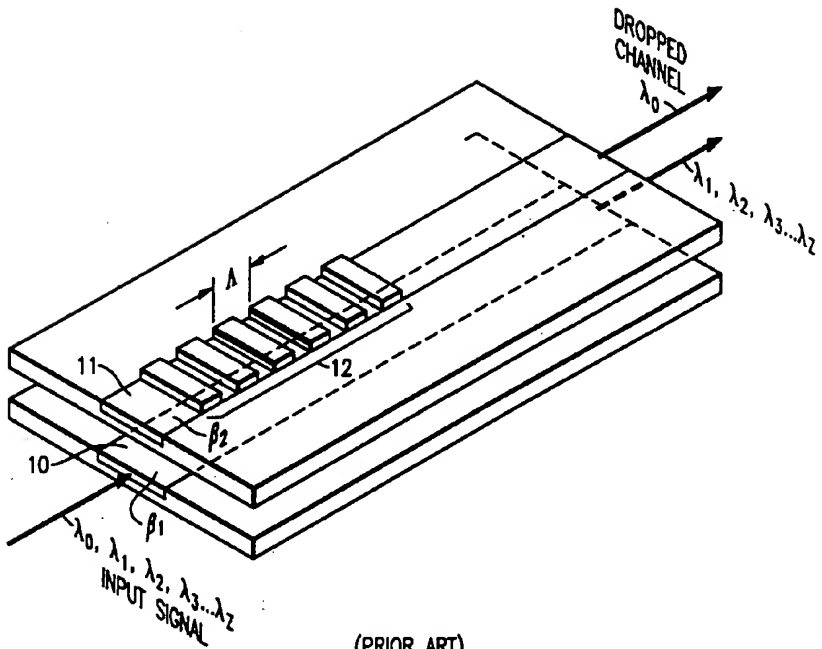 $$\lambda_{op} = \Lambda_{-1}(n_{2(TE)} - n_{1(TE)});$$
   where:
   $n_{2(TE)}$ and $n_{2(TM)}$ are the refractive indices at wavelength λ_{op} of one of said waveguides to the TE and TM modes respectively; and
   $n_{1(TE)}$ and $n_{1(TM)}$ are the refractive indices at wavelength λ_{op} of the other of said waveguides to the TE and TM modes respectively.
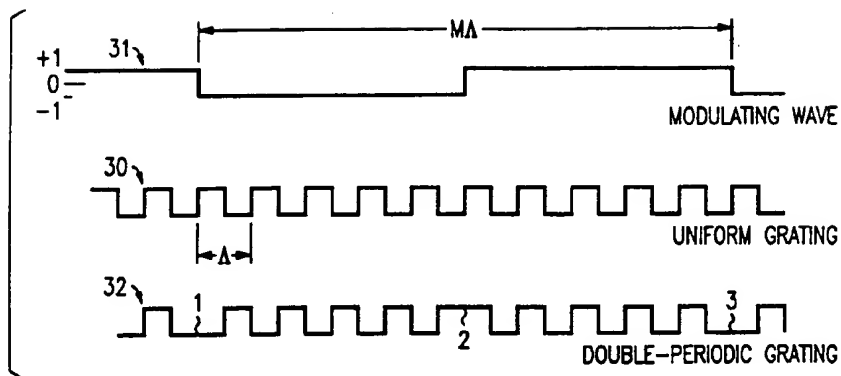
(PRIOR ART)

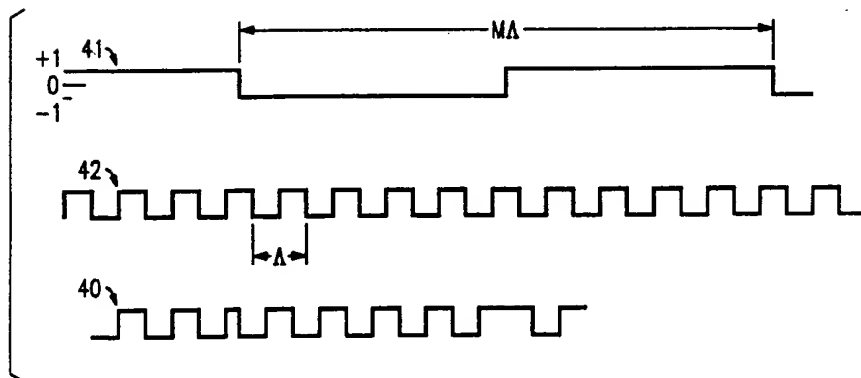*FIG. 1*

FIG. 2A

FIG. 2B

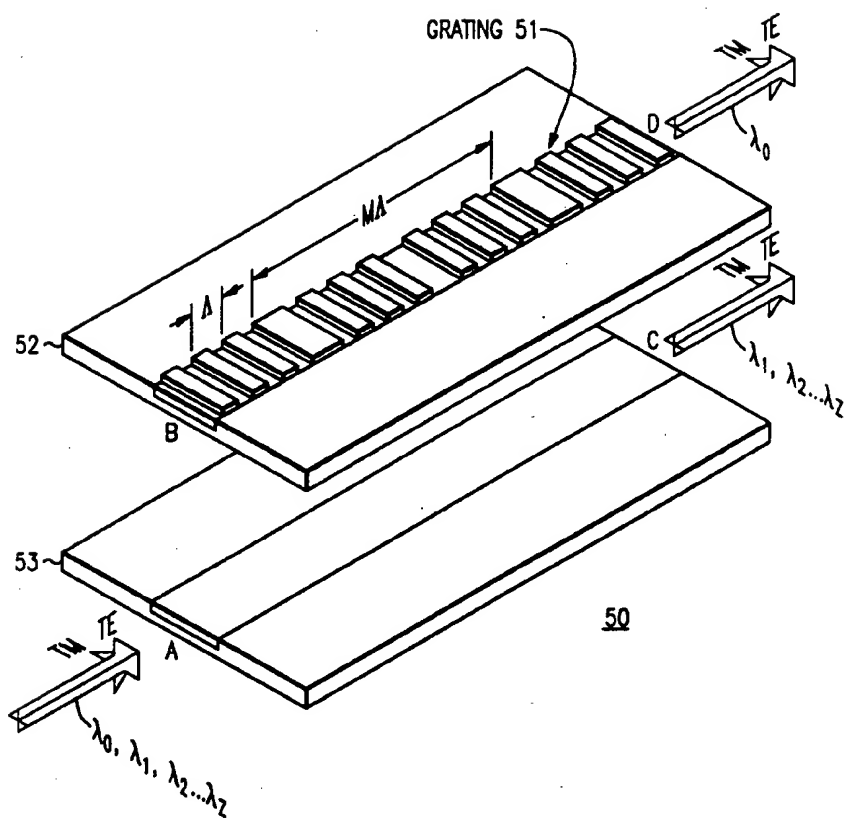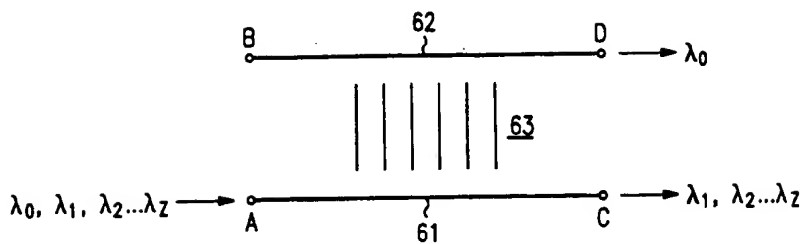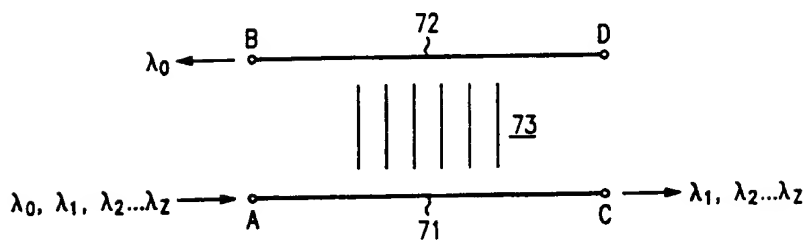**FIG. 3**

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 94 30 6422

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
P,X	APPLIED PHYSICS LETTERS., vol.64, no.18, 2 May 1994, NEW YORK US pages 2335 - 2337 HEISMANN ET AL. * the whole document *	1-6	G02B6/12
X	EP-A-0 559 192 (NTT) * page 6, line 10 - line 54; figure 6 *	1,2	
X	EP-A-0 547 859 (GEC-MARCONI) * column 2, line 37 - line 57; figure 2 *	1	
A	ELECTRONICS & COMMUNICATIONS IN JAPAN, PART II - ELECTRONICS, vol.74, no.10, October 1991, NEW YORK US pages 40 - 49 SAKATA ET AL. * abstract; figures 1,3,13 *	3	
A	PATENT ABSTRACTS OF JAPAN vol. 13, no. 4 (P-809) 9 January 1989 & JP-A-63 212 905 (NTT) 5 September 1988 * abstract *	4	TECHNICAL FIELDS SEARCHED (Int.Cl.6) G02B
A	JOURNAL OF LIGHTWAVE TECHNOLOGY., vol.10, no.1, January 1992, NEW YORK US pages 57 - 62 HAUS * page 58; figure 6 *	4	
A	JOURNAL OF LIGHTWAVE TECHNOLOGY., vol.7, no.11, November 1989, NEW YORK US pages 1641 - 1645 CREMER ET AL * abstract; figure 5 *	4	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	22 December 1994	von Moers, F